An Intelligent Hot-Desking Model Based on Occupancy Sensor Data and its Potential for Social Impact

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Abstract. In this paper we develop a model that utilises occupancy sensor data in a commercial Hot-Desking environment. Hot-Desking (or 'office-hoteling') is a method of office resource management that emerged in the nineties hoping to reduce the real estate costs of workplaces, by allowing offices to be used interchangeably among employees. We show that sensor data can be used to facilitate office resources management, in our case desk allocation in a Hot-Desking environment, with results that outweigh the costs of occupancy detection. We are able to optimise desk utilisation based on quality occupancy data and also demonstrate the effectiveness of the model by comparing it to a theoretically ideal, but impractical in real life, model. We then explain how a generalisation of the model that includes input from human sensors (e.g. social media) besides the presence sensing and pre-declared personal preferences, can be used, with potential impact on wider community scale.

Keywords: Hot-desking · optimisation

1 Introduction

Due to the increasingly digital world we live in, we tend to derive value and knowledge from as many sources of data as possible. Apart from any sociological parameters [1], there are two key factors that enabled that trend.

Firstly, it is the Internet of Things (IoT) or in other words the idea of providing internet connectivity, not only to established IT devices such as phones and computers but also to more 'traditional', seemingly non-IT devices such as air conditioners, fridges, chairs, locks etc [2].

Secondly, it is the rise of the so-called Big Data (BD). The constantly increasing amount of connected devices is generating an exponentially growing amount of data. This, in conjunction with the more and more sophisticated methods of analysing data and extracting knowledge, is bound to change the way we live [3].

Nowadays, numerous industries collect and analyse data for multiple purposes. From organisation with environmental mindfulness that try to measure and mitigate the impact of modern life-style on environment [4] to businesses that are after the most effective methods to reduce costs and increase profits.

adfa, p. 1, 2011.

These are only some technological trends, among the many that use data-harnessing concepts, often labelled as ‘Smart’. Due to their ubiquity, we can only expect similar examples to become more and more popular

1.1 Smart Buildings

Today, the notion of Smart Cities is popular, profitable and academically thriving. The underlying notion that a proliferation of connectable infrastructure, distributed, personal sensors and big data could create efficient, enjoyable and sustainable cities has become one of the defining schemes of the current age [2], [5], [6].

The application of the same notions and fundamentals within the bounds of a building instead of the whole city (i.e. Smart Buildings) has a relatively smaller growth although it is actually an essential part of the applications in a city level [7].

The existing work in the field of Smart Buildings, research tends to be more aligned with more traditional concepts such as ‘smart energy’, ‘smart structures’, ‘smart lighting’ etc.

1.2 Hot-desking

After the rise of the service sector in developed western economies, new large office workplaces were built by a new and increasingly diverse wave of consultancies and financial services. This, in conjunction with the rising rental costs in the large cities where these offices needed to be located [8] generated the issue of excessively high real estate costs for the companies.

As such, minimising the cost of large office areas became increasingly important. A popular idea emerged in the late 90s to replace territorial working systems - whereby each individual is directly associated with a specific desk - with an allocation system whereby those who attend the office on a specific day are given a free desk from a pool. The key value driver of this was that office sizes could be reduced up to 30% [9] depending on the tendency of the business to visit clients and collaborators outside the premises. A rise in part time working [10] further improved the benefit of non-territorial desk systems.

Today, the form of hot-desking that is usually met is simply employee-led: on attendance to the workspace, an employee chooses a free desk and claims it for the day. However, such schemes have had mixed success [11]. Literature’s criticisms on that can be categorised into three key aspects: (a) Ineffective management applying slow and inconsistent methods of distributing desks that can often even lead to misunderstandings about whether or not a desk if free [12], (b) Loss of working synergies which actually consists of the loss of collaboration and exchange of ideas due to not placing staff working on similar projects in close proximity, and (c) cultural and behavioural barriers which could include but not limited to the personalisation of an office (which is mostly lost in Hot-Desking environments) that could make the individual more comfortable and therefore more productive [13]. None of these parameters should look insignificant since even small variations (for example 1% decrease) in productivity have significant impact on even the smallest scales [14].

1.3 Intelligent Hot-desking

The rise of 'Smart' enablers provides a unique opportunity to fundamentally alter the nature of Hot-Desking by utilising increased data about the workplace, its occupants and their intentions and preferences. There is a considerable literature base that highlights that an employee's position, both in an absolute sense and in relation to other employees, has a strong impact on their behaviour and happiness in the workplace [15].

In principle, rather than a 'pegs into a slot' approach (i.e. simple linear desks assignment in a first-come-first-served basis), intelligent Hot-Desking would evaluate the best position for an employee to work based on an algorithm combining a number of weighted inputs. These inputs could include, but are not limited to:

Noise level [16] of workplaces, derived from acoustic sensors distributed across the office. There are workgroups that due to their work subject can only tolerate minimum noise (and usually produce minimum noise too) while other groups can work effectively in a noisy environment as well. The inability to effectively manage noise-sensitive and noise-making workgroups in an office can be one of the top 3 factors preventing their company from being more profitable [17].

Duration of stay derived from calendar data, or asked for at an on-arrival desk requests. Smaller 'touch down desks' can be useful for individuals staying for exceptionally short periods of time. This may further improve the floor area savings of traditional Hot-Desking.

Nature of work [18], which in the case of a very large staff group, could be derived from a system, where keywords for the type and project of work could be requested from individuals for a given day or calendar period. This element will enable workgroups of individuals with similar subjects and possibly similar goals to be formed which is proven to lead in greater productivity. Similar benefits would be realised for smaller projects too.

Environmental preferences [15] derived from various datasets, that could be generated, among others, from temperature and light sensors across the office. Many small but psychologically significant issues could be tackled this way. For example, individuals with a preference to warmer office environments could be placed further away from colder areas, whereas those with a mood that is more influenced from daylight on could be placed closer to the window.

Desk configuration, derived from asset location and management information and could include office equipment such as multiple monitors etc.

There could also be other kinds of personal preferences that could be, derived from occupant feedback (like for example level of satisfaction about previous desks given). Of course, the most appropriate combination of all the aforementioned parameters will always be heavily context-dependent

1.4 Purpose

While it is apparent from the outset that distributing desks intelligently is indeed possible, little research exists on how optimization might look in practice, or the value it could bring to the workplace.

Within this study we will explore the potential for Intelligent Hot-Desking to result in superior working conditions (in the form of increased productivity) in comparison to a Traditional Hot-Desking Systems.

To demonstrate this we will use the distribution logic of ‘work theme’ within a demonstrator context of an engineering consultancy’s commercial office, facilitated by primary data.

As such our objectives are as follows:

1. Establish a modelling framework, context and distribution algorithm for our scenario.
2. Observe the practical workings of an Intelligent Hot-Desking System throughout a simulated day.
3. Deduce an estimate for the improvement in productivity that Intelligent Hot-Desking Systems could bring over Traditional Hot-Desking Systems.
4. Discuss the potential barriers and enablers to implementation of Intelligent Hot-Desking Systems.
5. Explore the potential for expanding the model to inter-organisational scenarios and professional social networks.

2 Related Work

The bibliography that is related to Hot-Desking can be mostly categorised into three main research topics. Firstly, it is the topic about the impact of Hot-Desking on the health status of the employees. The second category is related to the examination of the evolution of the workspaces throughout the years. Finally, the third one is about the importance of the workplace for the employees and its impact on their productivity or even on the mind-set and their sense of team spirit. Existing studies were not found to have similarities to this one. Related work that is presented here is about different use cases that the concept of Hot-Desking is used for and although they can be seen as somewhat similar to our work (by various criteria that are explained below) they are still remote enough.

It is worth mentioning that the definition of Hot-Desking is somewhat vague and therefore some conflicts can often occur among different authors [19, 20]. However, the term ‘hot desks’ is most commonly used in order to express ‘desks that can be used each time by a different user’ and this is the definition that we will use in this work.

It is often due to this controversy on the definition, that the topic of Hot-Desking is related to Sit-and-Stand desks and therefore to employees’ health. Authors of [21] for example relate hot desks with standing desks and they look into the impact that this kind of desks has on the sedentary work time in an open plan office. According to the findings, these desks did not have a great impact on the sitting working time of the employees.

In a similar fashion, the effectiveness of sit-stand workstations in terms of their ability to reduce employees' sitting time is studied in [22]. However, the findings from this 'Stand@Work randomised controlled trial pilot' differ significantly from the previous one since that study shows that these kind of desks can indeed reduce sedentary work times in the short term. It should be mentioned though that authors note the necessity of larger scale studies on more representative samples in order for the exact impact of sit-stand workstations on the health of individuals to be more accurately determined.

In [23], an attempt for results of six related pieces of research to be compared is made. All six of them are about the effect that some interventions at the workplace can have on the sitting habits of the employees during their working hours. The interventions vary from one another and in all of them, sitting time had not a significant decrease due to the aforementioned interventions.

Authors of [24] relate hot desks with sit-stand desks. These are desks that are considered 'hot' according to the definition that we adopt, with the specificity of being used in a standing position. The objective here was to examine whether the use of these desks along with awareness regarding the importance of postural variation and breaks would manage to cause better sedentary habits for the employees. The results showed that the adoption of these desks led to a better sedentary behaviour.

In a fashion similar to the previous works that were presented, authors of [25] experiment on the effect that the installation of sit-stand workstations could have on the reduction of worker's sitting times. In this study the results were very encouraging since the adoption of the sit-stand workstations was astonishing with huge impact on the sitting times ('Sitting was almost exclusively replaced by standing'). However, although the strong acceptability of these workstations, there were some design limitations that should be considered in future attempts.

All the aforementioned pieces of research belong to the first of the three categories that the bibliography can be summed up to (i.e. the impact of Hot-Desking on the health status of the employees). Below, we present characteristic representatives of the remaining two categories. Representatives of the second category (i.e. examination of the evolution of the workspaces throughout the years) followed by the ones related to the importance of the workplace and its impact on the productivity, mindset and team spirit of the employees, which is the third category.

The evolution of the workplaces is examined at [19]. In particular, its authors investigate the rate of adoption of modern-type workplaces, including but not limited to Hot-Desking. It is interesting though that the authors define 'hot desks' as 'desks which workers have to book in advance to use' while the definition we adopted resembles more the definition that authors use for 'collective office' which according to them is 'facilities that are shared and used on an as needed basis'. Combining many sources of evidence, authors conclude that although workplaces tend to differ more and more from the typical conventional ones that were used in the past almost exclusively, this is happening with a slower rate than some claim. The findings of this study are mostly confirmed by the findings of [13]. According to the evidence of the latter, office work is increasingly differentiated from the traditional workplaces although for the majority of employees, work still corresponds to a designated place.

In [26] we meet once more the concept of Stand@Work, but this time it is not its impact to the sedentary patterns that is investigated. Instead, the objective was to qualitatively evaluate the willingness of the employees to adopt new types of workplaces, the feasibility of such a venture and the general perception of employees about the use of sit-stand workstations. The whole scheme was generally perceived as both acceptable and feasible although studies with different populations and settings need to be made.

Another study [26], considers Hot-Desking within the grand scheme regarding the societal changes in the ownership of space. The aim of this study is to sociologically analyse the emergent sociospatial structures in a Hot-Desking environment where space is used by more than one users exchangeably. The study results in two interesting findings. Firstly, the find that the perception of mobility may not be spread evenly among the employees, resulting in two different groups of them: the settlers (i.e. the most resistive to change) and the 'hot-deskers'. Secondly, according to the findings, the routine of mobility itself can generate additional work and a motion of marginalisation to the adopters.

For the third and final category of related studies, we can include [11] as well, although it belongs to the previous category too. That is because its findings are related not only to the evolution of workplaces but also to the impact that this has on the adopters, from multiple perspectives.

Apart from that study, there is also [14] which examines the impact of Hot-Desking on organisational and team identification. The study tested the level up to which the organisational and the team identity are affected by the way desks are assigned and secondly the impact that physical arrangements have on the level of engagement with the organisation. According to the results, team identity is more salient than organisational identity when a traditional desks assignment is applied whereas organisational identity is more salient when Hot-Desking is applied. The findings also denote that physical arrangements not only have significant impact on the level of engagement of the employees, but also on the on the type and focus of organisational participation.

2.1 Elements of Originality

It is obvious from the related work that is presented, that research in the field is relatively undeveloped, especially when we consider when these studies were made. But most importantly, there is a big gap in the bibliography when it comes to the research of the connection between the Hot-Desking and the productivity of the adopters. As shown already, studies on that connection are very scarce and even then it is only an indirect connection that researchers usually study. Now researchers almost always examine the implications of Hot-Desking on health, or more specifically on the sedentary habits of the adopters. Even the study on profitability, which is one of the reasons that Hot-Desking was initially developed, has been ignored due to the aforementioned approaches.

Furthermore, the nature of the existing approaches is such that no modelling is performed in order to utilise Hot-Desking in the best possible way, both in terms of organisation's profitability and employees' productivity.

What we offer is a different approach. It is a model that based on occupancy data of the employees, calculates in real time and suggests which desk has to be assigned to every employee at the time they arrive at the organisation. The model decides which desk will make the employee as productive as possible based not only on the project that they are working on but also on the projects that all the remaining employees are working on at that period of time. That way, not only employees find themselves working in the most productive environment possible without having to decide the sitting arrangements themselves (with any disadvantages that this would entail in terms of inter-employee relationships) but also the organisation will have a double benefit as it will make profit not only due to the number of desks that will not need to use anymore (desks will be less than the employees while still covering their needs), but also due to the fact that all employees will work under optimal productivity conditions.

3 Modelling

We will principally address the situation as a discrete events simulation handling the grid of desks as a grid of slots, each of which can be occupied by only one employee at a time and is either free or occupied.

On an employee's arrival, the model will decide the best desk for the individual to be assigned to. Every individual's productivity affects and get affected by individuals close to them (more on the notion of productivity are explained below). The positioning will be such that the total productivity of the grid of desks, which is the sum of the productivities of the employees of all desks, is maximised.

The simulation will run for 1 day during which many properties of the employees are logged (their desk, their individual productivity, the time they spent in their offices and the total productivity of the grid). The time is so accurately measured that is practically impossible that two incidents (each of which can be either an arrival or a departure) can happen at exactly the same time.

3.1 Individuals

For the behaviour of individuals we will be using primary observational data collected from an anonymised office of an engineering consultancy. The observed scenario has the following characteristics:

- Office grid: 144 desks (12x12)
- Total number of employees: 180

In practice, the time spent in the office will vary distinctly among individuals. Support staff, such as HR and Accounting are unlikely to ever leave for off-site work. Low and middle-ranking general employees are likely to attend client sites on occasion, and high-ranking staff, whose role include client relation management and thought-leadership, are likely to regularly leave, and be, out of office. These are of course generalisations and the exact spread and nature of office attendance will depend on organisational size, office size, industry and organisational culture.

By observation, supported by reasonable assumption, we can see that flow to the office in our scenario is a combination of (a) traditional morning and evening peaks for entrance and exiting to the office and between these (b) a lesser, broader flow of assorted leaving and re-entering of the office for various business engagements.

The first is relatively simple to model; the latter will require considerable simplification. Fitting normal distributions, we will estimate the probability of an individual entering the office over the course of the day and the probability of an individual who is in the office, leaving an office, as the sum of the following weighted distributions:

*Arriving: w1*A+w2*B ; w1+ w2=1*
A: Norm (8.5, 1), w1= 0.7
B: Norm (13, 5), w2= 0.3
*Leaving: y1*A+y2*B ; y1+ y2=1*
A: Norm (18, 1), y1=0.7
B: Norm (13, 5), y2= 0.3

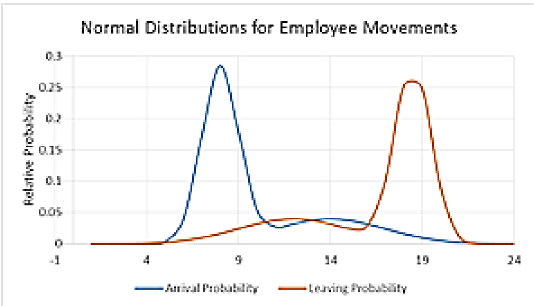

Fig. 1. Graphs of the distributions that describe arrival and departure times of employees.

Figure 1 displays this graphically. These estimates will serve as a reasonable assumption for a generic context. However, variation will exist between different companies and different industries.

We will also simplify as to there being no inter-relation between arrivals and departures of individuals. In other words, if an individual arrives late to the office, they are just as likely to leave for a meeting as someone who has been there since early. We will deem this an acceptable simplification. Furthermore, employees will only be able to enter and leave the premises once. The probability distributions will in effect simulate real return visits as new individuals.

Lunch and other temporary breaks have been ignored as observation demonstrates that desks remain allocated during these periods.

In the wider group of staff from which our sample is taken, there were five work types. The distributions of these work types (i.e. the probability of random employee to belong in any of these types) in our primary data are thus: Type A: 40%, Type B: 30%, Type C: 15%, Type D: 10%, Type E: 5%. If some day, other than the one we model, employees change workgroups, this probabilities will change too. This specific distribution may not be the reality in all samples. However, our research suggests this is not unusual for the industry from which the examined organisation is from [27].

3.2 Productivity

There is no documented method for assessing the level or quality of interaction between two individuals in the workplace and the distance between their desks. As discussed, research has simply shown that the quality, with respect to pragmatic business ends, appears to be higher when 'the right' individuals are in a 'close proximity' since the ability to speak to one another is regularly cited as a beneficial consequence of sitting near another individual [7]. Thus, we will use the behaviour of noise to model these relationships since noise levels can determine the quality of the aforementioned communication. In particular the square law will be used to describe noise impact with respect to distance from the noise generator.

As such, we depict individuals as being able to have a positive productivity influence, following square-law decay, to other relevant (i.e. of the same work type) individuals in their proximity. Of course, when individual i influences individual j, j also affects i in the same way, since this is only distance and workgroup dependent. Influences will sum linearly when several sources of influence are combined. We model irrelevant staff as having neither positive nor negative effect.

We assume desk units have a size of 2.5m boundary from observation in our scenario, and that noise values are measured 0.5m from the centre of the unit – again, a realistic point of seat from observation of scenario. We will then use basic square law as an estimate:

$$I_2 = \left(\frac{d_1}{d_2}\right)^2 \times I_1,\ I_3 = \left(\frac{d_1}{d_3}\right)^2 \times I_1 \tag{1}$$

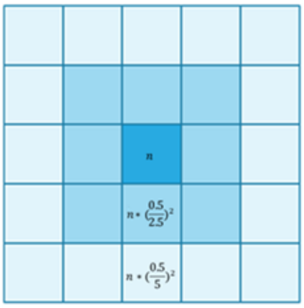

Fig. 2. Representation of the effect of one employee to the productivity of their neighbours.

For simplicity we ignore diagonal inaccuracies. Value of n will start at 25, to produce the values that are demonstrated below:

1st Row Proximity: 1
2nd Row Proximity: 0.25
3rd Row Onwards: (neglected for simplicity)

This is also depicted in Figure 2 which uses the square law formulas (1). What this practically means is that every employee has a zero productivity when arriving the premises and after the algorithm has assigned a desk to that individual, every employee's productivity becomes:

$$Prod(emp) = 1 \times n_1 + 0.25 \times n_2 \tag{2}$$

Where, n_1 is the number of employees of the same workgroup that occupy desks (out of the 8 in total) neighbouring to the employee whose productivity we measure (i.e. first row neighbours) and n_2 is the number of employees of the same workgroup that occupy desks (out of the 16 in total) that are next to the neighbours of the employee whose productivity we measure (i.e. second row neighbours).

It can be easily observed that if an employee is surrounded in the first row on all sides by other employees of the same workgroup, a value of 8 (8x1) is achieved. If the same applies for the second row then a value of 12 is achieved (8x1+16x0.25), which is the maximum achievable productivity for any individual. Therefore, there is obviously a synergy: when there are two individuals, they improve each other's working environment, so the total 'quality of environment' increases from 0 (with one person) to 2 (with both).

According to formula (2), when an employee is not surrounded by an employee of the same workgroup, then the productivity of this particular employee is equal to zero. That does not mean, that this employee is not contributing at all, but what this model computes is the best way to allocate employees to desks and for that reason, even assuming that every employee's initial productivity (i.e. when there is no employee of the same workgroup around) is equal to $prod_{init}$, if it is the same for everyone (and it cannot be assumed that the individuals are not equally productive when working alone without any measurements to support that), then that would offer nothing to the model and the optimal solutions would be exactly the same. That would happen because when comparing between two possible allocations A_1 and A_2 of h employees where

$$TotalProductivity(A_1) = P_1,\ TotalProductivity(A_2) = P_2 \tag{3}$$

Then, with the addition of $prod_{init}$, we would have

$$TotalProductivityNew(A_1) = P_1 + h \times prod_{init} \tag{4}$$

$$TotalProductivityNew(A_2) = P_2 + h \times prod_{init} \tag{5}$$

Therefore, it is obvious that the result of the comparison between *TotalProductivity*(A_1) and *TotalProductivity*(A_2) would be always the same as the result of the comparison between *TotalProductivityNew*(A_1) and *TotalProductivityNew*(A_2).

3.3 Intelligent Hot-Desking Distribution Process

Possible methods by which we could evaluate the distribution of the desks in this system include:

- *On-arrival, current-state individual optimisation*: In a system where no pre-advice is given as to who will be in and who shall not, desks are allocated aiming to maximise the productivity of the arriving individual based on information for the exact moment they enter, hoping conditions stay favourable.
- *On-arrival, current-state group optimisation*: In a system where no pre-advice is given as to who will be in and who shall not, desks are allocated aiming to maximise the total productivity of all currently in the office, based on information for the exact moment they enter, hoping conditions stay favourable.
- *Full-term, group optimisation*: In a system where pre-advice is given as to who will and will not be in (including duration of stay), desks are allocated aiming to maximise the total productivity of all individuals intending to arrive that day.

It is clear that the more advanced the system, the more ideal the seating locations and the higher the productivity overall. For purposes of computational simplicity, and to avoid reviewing a distribution process with significant cultural barriers to implementation, we will use the second method in this instance.

By observation it can be considered that systems 1 and 2 will struggle with early arrivals as many permutations are identical – yet their decision will strongly influence the rest of the day. As such a tie-breaker logic is required. After experimentation of several tie-breaker systems, the most effective was chosen. The first (out of the ones that are present at the premises; not including the ones that have left) representative of every workgroup that arrives will be sent as close to a predefined extremity of the office that has been preassigned to that workgroup as possible. These will be the four corners (workgroup A at top left, B at top right, C at bottom left and D at bottom right) and the centre of the grid for workgroup E. In effect, the distribution has a disposition to form colonies with enough space to expand before starting interfering with each other, plan that will lead to high total productivity.

3.4 Variations of the Model

The model under testing has actually four versions which can be perceived as four different models. All the aforementioned characteristics are common across all models. Their differences are the following:

- *Model 1:* When an employee arrives, the algorithm assigns an empty desk to them. If there is no free desk, the employee leaves the premises and does not return the same day. When the employees leave the premises, either because it is time for them to leave or because there is no free desk, they do not return the same day.

- *Model 2*: When an employee arrives, the algorithm assigns an empty desk to them. If there is no free desk, the employee goes at the end of a First-In-First-Out queue. The employee leaves the queue if it is time to leave the premises or if there is a free desk for them (whichever comes first). When the employees leave the premises, either because it is time for them to leave or because there is no free desk (or both), they do not return the same day.
- *Model 3*: When an employee arrives or when an employee departs, all the employees (apart from the one that is leaving, in the case of departure) are reassigned (possibly different) desks of the grid, so that the maximum possible productivity can be achieved with the given employees at that time. When an employee arrives and there are no free desks, the employee leaves the premises. When the employees leave the premises, either because it is time for them to leave or because there is no free desk, they do not return the same day.
- *Model 4*: When an employee arrives or when an employee departs, all the employees (apart from the one that is leaving, in the case of departure) are reassigned (possibly different) desks of the grid, so that the maximum possible productivity can be achieved with the given employees at that time. When an employee arrives and there are no free desks, the employee goes at the end of a First-In-First-Out queue. The employee leaves the queue if it is time to leave the premises or if there is a free desk for them (whichever comes first). When the employees leave the premises, either because it is time for them to leave or because there is no free desk (or both), they do not return the same day.

It is worth clarifying that an employee can leave the premises while waiting in the queue, for the same reasons that they could leave while being in a desk (i.e. external business commitments etc.)

Model 1 has been actually tested at [28] when it was compared to the following three variations:

- Individuals come in and are allocated a desk randomly among the free desks, with no logic applied. If there is no free desk, they leave the premises and do not return the same day.
- Individuals come in and are given a desk in a ‘closest desk free’ (to the top left of the office) system. Essentially, this is the linear, ‘pegs into a slot’ distribution that has already been discussed. If there is no free desk, they leave the premises and do not return the same day.
- For means of understanding its influence, we will simulate a distribution that simply has the ‘extremities’ tie-breaker logic only, and aims to throw individuals as close to the predefined extremities, and does none of the evaluation in the intelligent system. If there is no free desk, they leave the premises and do not return the same day.

As a result of that comparison, Model 1 was found to be the best (i.e. leads to a distribution of employees with higher total productivity than the total productivity of the distribution that the remaining three variations lead to).

The aim of this work is to take that previous study one step further and compare Model 1 with variations like Model 2, Model 3 and Model 4. Although it is obvious that Model 3 and Model 4 are not applicable in real life, they are still useful for comparison because they represent the ideal models. That is because these two models solve an inevitable problem that Model 1 and Model 2 have. Although Model 1 encourages the creation of colonies by employees from workgroups A, B, C, D and E (which is the best way to result in a high total productivity since individuals increase their productivity when they are close to other individuals of the same workgroup), inevitably there will be times where a colony will have a free desk in it, due to a departed employee of that colony, which will be occupied by an employee of another workgroup who cannot be placed closer to their own workgroup because there are not any free desks close to that group. That will create desk grids with individuals that are not placed in the most optimised way. However, this is inevitable unless all employees are rearranged frequently during the day, which is impractical and inapplicable in real life. However, it is useful to check how much better the results of Model 3 and Model 4 are when compared to Model 1 and Model 2 respectively, because if the difference is small that would mean that Model 1 and Model 2 are actually very close to the absolute optimal and therefore work great.

4 Results

In this section the results of Model 1, as described before, will be demonstrated, analysed and compared to Model 2, Model 3 and Model 4. Figure 3 depicts the impact of all models on the total productivity of the organisation throughout the whole day.

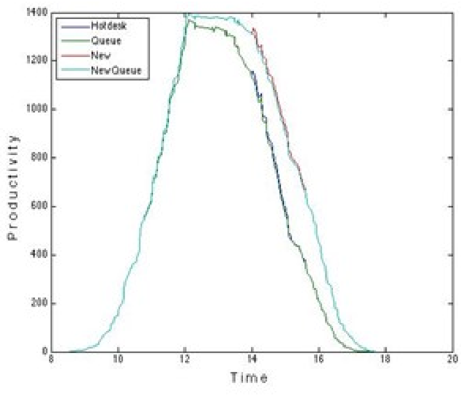

Fig. 3. Comparison of all 4 models with respect to the productivity they result in.

The equivalence of the aforementioned models to the ones on Figure 3 is: Model 1 = Hotdesk, Model 2 = Queue, Model 3 = New and Model 4 = NewQueue. Judging by this figure, we can tell that the addition of queues not only has very small impact on the productivity, but also that slight impact is not always positive (it is not easily visible in this size of the figure but it is positive sometimes) but it can also be negative. That may not always be the case with queues, but even in this case it should not be seen as an unorthodox fact. The reasoning behind that phenomenon can be explained with the following example. Since the employees are less than the desks, there can be times where all desks are occupied and employees keep arriving. In the scenario that includes queues, if employee e_1 arrives and there are no free desks, e_1 will go last in the queue. If employee e_2 arrives later and there are still no free desks, e_2 will go last in the queue, behind e_1 (providing that e_1 has not left the queue because it was time to leave). By the time there is a free desk for e_2, it can be the case that e_2 has already left while some other employees, like e_1 for example, may have found a desk by then. Therefore, due to the queues, employee e_1 was advantaged compared to e_2. However, if there were no queues, there would be higher chances for e_2 to find a desk on arrival because if some other employee, like e_1, had arrived before e_2 and had not found a free desk, they would have left, instead of waiting of waiting in a queue in front of e_2. Thus, in the case of queues, e_2 would be disadvantaged compared to e_1 even if e_2 had more to offer than e_1 to the total productivity. This example demonstrates situations that can occur and lead to Model 2 resulting in less productivity than Model 1 (and Model 4 less than Model 3, respectively) for some periods of time. To sum up, queues maintain the first-come-first-served logic of the desks assignment whereas absence of queues can break that rule (like in the example where e_2 could have found a desk before e_1, if e_1 had departed just after their arrival) which can sometimes be beneficial for the total productivity.

However, the most important finding that comes out of this figure is the fact that Models 3 and 4 do not produce significantly better total productivity than Models 1 and 3, respectively, throughout the biggest part of the day. In other words, the, not applicable in real life, Models 3 and 4 that produce the best possible total productivity, seem to perform only slightly better than Models 1 and 3, respectively. The only periods of time, that Models 3 and 4 outperform Models 1 and 2 significantly is towards the end of the day when not many employees are still at their desks and if they have been arranged according to Models 1 or 2 then they will most probably be disorderly spread. And still, this difference is significant more in percentage terms and less in absolute numbers That is a huge success for Models 1 and 2 and a very good indicator that there is not much room for improvement of the algorithm, providing that the fundamental assumptions of the model remain the same. A possible and simple way to make Model 1 (resp. Model 2) almost equivalent to Model 3 (resp. Model 4) is to rearrange all employees only once (which is viable) in the afternoon, when the impact of the many departures is already apparent. After that time, although Models 3 and 4 will continue to perform better than 1 and 2, the difference will be even smaller. Figure 4 actually demonstrates that idea in practice for Model 1 ('Hotdesk') compared to Model 3 ('New'). The reassignment occurs at 3pm and its result is demonstrated on Figure 5.

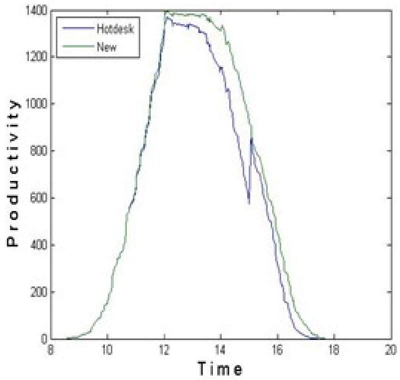

Fig. 4. Comparison of Model 1 with a rearrangement at 3pm ('Hotdesk') to Model 3 ('New')

In order for the difference between Model 1 and Model 3 to be seen in practice, snapshots from the distribution of employees among the desks is provided at 3pm, when a significant amount of employees has already departed and since there are not many that are still to come, most of the workgroups are not optimally spread across the desks, in case of Model 1, but are still optimally spread in case of Model 3. This is not a contradiction to the previous explanation of Figure 5 because it is expected that the snapshot at 3pm of the modified version of Model 1 (with one rearrangement at 3pm) will be the same as the snapshot of Model 3, at the same time (3pm).

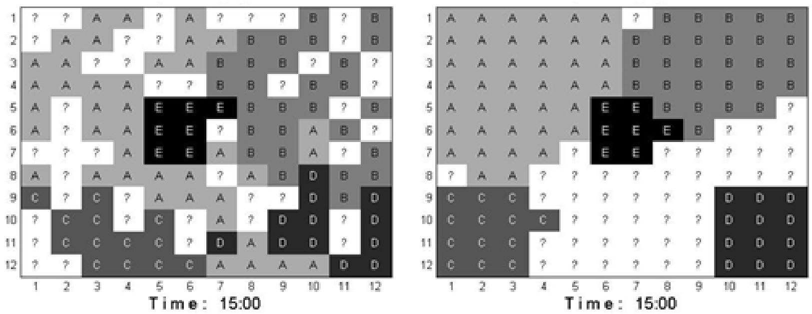

Fig. 5. Snapshots of workgroups allocation for Model 1 (left) and Model 3 (right) at 3pm (? = Free).

Converting the gain in productivity into gain in profitability is not always straightforward. One of the reasons is that the gain in productivity will lead to gain in working time which is not always sure if it will invested on productivity again and in what percentage. Making very austere assumptions about the percentage of the saved working time that will be reinvested in productivity (0.1% - 5%) and based on Table 1 [29], we calculate the years that will need in order for the investment of installing the system to run the aforementioned models to be fully repaid. It is worth mentioning that the cost of such an investment is considered to be in the neighbourhood of £15,000 [30].

Table 1. Correspondence of productivity increase (%) to actual annual profit.

Percentage Productivity Increase	Annual Value	Investment Repayment Time (Years)
0.1%	£ 15,502	0.97
0.2%	£ 31,004	0.48
0.3%	£ 46,505	0.32
0.4%	£ 62,007	0.24
0.5%	£ 77,509	0.19
0.6%	£ 93,011	0.16
0.7%	£ 108,512	0.14
0.8%	£ 124,014	0.12
0.9%	£ 139,516	0.11
1.0%	£ 155,018	0.10
2.0%	£ 310,036	0.05
3.0%	£ 465,053	0.03
4.0%	£ 620,071	0.02
5.0%	£ 775,089	0.02

5 Conclusions and Future Work

Out of the three methodologies that were described earlier (i.e. (a) On-arrival, current-state individual optimisation, (b) On-arrival, current-state group optimisation and (c) Full-term, group optimisation) we modelled the second one. That is because it is more sophisticated than the first methodology and there are only specific applications where this could potentially be preferred. The third methodology, would require even more data and forecasting on the arrival and departure times which means that there would be the danger of resulting in big inaccuracies. Furthermore, an adjustment period is required before such a model can be trusted. Using the second methodology we managed to provide a realistic and productivity-oriented way of assigning desks to individuals at a workplace. Additionally, not only did we confirm that this method can outperform other common ways of desk assignment, but we demonstrated that its effectiveness is comparable with a model that was designed to result in the optimal outcome. Finally, the profit implications for the corresponding organisation were analysed and the adoption of the model was found to be an easily repayable investment.

However, we aspire to use this modelling for greater social impact that transcends organisational boundaries. At the heart of our model is the assumption that sensing data and personal preferences can feed into an intelligent platform that will bring together the most suitable co-workers under their preferred working conditions. But there is no constraint to assume that these persons must be working within the same organisation. In fact, if we apply this model in facilitating the desk allocation in the scenario of a business incubator, it could bring together complementary skills and expertise as well as personality types. To that effect we intend to develop the model further to include inputs from human sensors (e.g. social media updates), besides the 'hard' sensing data which may include e.g. presence and location, as well as predefined personal preferences and maybe calendar entries. We have planned an amendment that will be able to foster meaningful clustering in an incubator setting and hopefully facilitate co-working between entrepreneurs with compatible ideas and complementary skills.

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